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Surface Technology Systems Limited,
Imperial Park,
Newport,
Gwent,
NP1 9UJ

Patents ADP number *(if you know it)*

5534151002

If the applicant is a corporate body, give the country/state of its incorporation

United Kingdom

4. Title of the invention

Plasma Processing Apparatus

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Wynne-Jones, Laine & James,
Essex Place,
22 Rodney Road,
Cheltenham,
Glos.
GL50 1JJ
United Kingdom

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Signature Wynne-Jones, Laine & James Date 10.12.98

WYNNE-JONES, LAINE & JAMES

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Plasma Processing Apparatus

This invention relates to a plasma processing apparatus, in particular, although not exclusively, one for reducing and/or homogenising the ion flux of a plasma without affecting the radical number density of the plasma.

When etching thin films or bulk material on a silicon wafer or work pieces of other material, it is important to be able to achieve simultaneously a high etch rate, an accurate trench profile, and good uniformity of the etch between different areas of the wafer.

A particular method to achieve highly anisotropic etches for high aspect ratio trenches is to use a switched process in which an etch step is alternated with a deposition step. Such a method is disclosed in WO-A-94/14187, EP-A-0822582 and EP-A-0822584.

In the case of deep trench silicon etching, a passivating layer may be deposited on all surfaces of the trench, during the deposition step. During the initial part of the etch step, the passivating layer will be removed preferentially from the bottom of the trench by ion bombardment. This then allows the silicon to be removed by an essentially chemical process, from the bottom of the trench, during the remainder of the etch step. Alternating deposition and etch steps, allows a high aspect ratio trench to be etched, contrasting with the use of the etch step alone which would result in a predominantly isotropic etch.

There are a number of factors which will influence each

step of the deep etch process. In particular, during the etch step, the density of radicals will affect the rate of etch of exposed silicon, and the density, energy and direction of positive ions will affect where and how fast the passivating layer is removed.

For deep trench etching it is desirable to utilise a plasma processing apparatus which produces large numbers of radicals to achieve a high silicon etch rate. Indeed, conditions ideal for the etching step may not be ideal for the passivation step. At the same time, sufficient numbers of very directional, relatively low energy ions should be produced to remove the passivating layer from the bottom of the trench without at the same time removing a significant thickness of the photoresist mask. Clearly, once the mask has been etched away it is not possible to continue with the same degree of pattern transfer from the mask.

A plasma processing apparatus will produce both ions and radicals and the number of each will, in general, increase as the power input into the apparatus is increased. The relative numbers of radicals and ions may change with power input conditions, but will not necessarily be the ideal balance required for the deep trench etch.

The present invention, at least in some embodiments, discloses techniques and devices to adjust the balance of numbers, to modify spatial distributions and allow "discrete" optimisation of both steps (etch and passivation), to ensure the etching of accurate trench profiles, with good uniformity of etch between different

areas of the wafer. Methods of largely "decoupling" the generation of the etch species from that of the passivation species are presented.

According to a first aspect of the present invention, there is provided a plasma processing apparatus comprising means for striking a plasma in a chamber having a gas inlet and a support for a substrate, wherein the apparatus further comprises attenuation means for reducing and/or homogenising the ion flux from the plasma substantially without affecting the radical number density.

A plasma processing apparatus may refer to an apparatus in which the process plasma is created and maintained by the inductive coupling of RF power into it, and bias is applied to the substrate (which may be a wafer/workpiece) by a second RF power source. However, this description is for the purpose of explaining the concepts involved, and is not intended to preclude apparatus in which plasma is generated by other means such as ECR, Helicon, Capacitive, DC, and pulsed power discharges etc, nor to preclude apparatus in which bias is applied to the substrate by DC or RF means whether pulsed or not.

The attenuation means may be any suitable attenuator or filter, and particular preferred examples are described below.

The plasma processing apparatus may further comprise means for alternately providing an etch gas and a deposition gas to the chamber. The etch and deposition gases may be fed via the same or separate distribution systems.

Whilst SF_6 is used as an example of the etch gas, other etch gases may be used, and these are well known to those skilled in the art.

In a preferred embodiment, at least a portion of the chamber is formed of a dielectric material. Particularly, it is preferred that an upper part of the chamber is formed of a dielectric material, where the support is in the lower part of the chamber. Preferably, an antenna is positioned externally adjacent the dielectric portion and this may serve to create a plasma production region in the chamber. The antenna may be used to inductively couple RF power into the plasma which is formed inside the apparatus. The frequency of the RF power is typically 13.56 MHz, but other frequencies may also be used.

The support is preferably energised from a second RF supply. It is well known by those familiar with such systems, that the application of RF power to a substrate which is immersed in a plasma results in the formation of a quasi DC bias on the substrate, such as to accelerate positive ions towards the substrate.

The attenuation means may be positioned above the substrate on the support, and it is particularly preferred that it is positioned between the plasma production region and the substrate.

The attenuation means may comprise a magnetic portion. In particular, the attenuation means may comprise one or more permanent magnets. Alternatively, the attenuation means may comprise means for creating an electromagnetic

field. For example, the means may comprise a current carrying conductor. This has the advantage over using permanent magnets in that by adjusting the current passing through the conductor, the magnetic field strength may be adjusted as appropriate for any particular process. Alternatively, the attenuation means may comprise both one or more permanent magnets and means for creating an electromagnetic field so that a chosen proportion of the field strength is constant from the permanent magnets, but may be increased or decreased by altering the current creating the electromagnetic field. As the electromagnetic field is only a proportion of the total field, the required current will be reduced when compared with that needed to create a total field, leading to a requirement for a smaller power supply and smaller cross-section conductors.

In one embodiment, the attenuation means may comprise one or more tubular members carrying permanent magnets or conductors to form an electromagnet. These may be parallel to each other and, for example, may be parallel to the surface of the support. Additionally, or alternatively, the attenuation means may be substantially parallel to the side walls of the chamber, although this should not preclude the use of attenuation means for which the spacing from the wall of the chamber varies along their length. In one embodiment, the attenuation means extends from the lid of the chamber to a plate member extending from a wall of the chamber, preferably having a centrally located aperture therein. As an alternative, the upper end of the

attenuation means may terminate on a plate member. Therefore, the attenuation means in such an embodiment may or may not extend all the way between the top and bottom of the dielectric window.

The attenuation means may be cooled. Any suitable cooling medium may be used but specific examples are forced air and water. The cooling medium may be passed through the tubular members to ensure that the magnets are not subjected to high temperatures. A distribution member, for example in the form of a manifold, may be provided to distribute the cooling medium to the attenuation means.

The attenuation means and/or the distribution member may be electrically biased.

In one embodiment, the attenuation means may comprise one or more strong magnets and these are preferably positioned outside the plasma chamber, although alternatively they may be positioned just inside the chamber and are preferably cooled. Again, in such an embodiment, the strong magnets can be in the form of permanent magnets, electromagnets, or a combination of both.

The attenuation means may comprise a sheet member having a plurality of apertures therein, for example in the form of a "grid". The grid may have varying sizes of apertures at different positions and may have solid sections. In this embodiment, the sheet member is preferably metallic.

The purpose of the sheet member is to attenuate the ion flux reaching the substrate due to ion loss on the sheet

member and also, if it is of metallic construction, to define an equi-potential plane for the plasma, so that ions which are accelerated towards the wafer pass through a well defined potential gradient between two parallel surfaces. The sheet member may be biased electrically with respect to the metallic components of the chamber - a negative bias on the sheet member will aid in the collection of ions.

If the overall "transparency" of the sheet member is low, there is the hazard that deposition may occur on it resulting in a reduction of deposition rate on the substrate during the deposition step. This factor may be reduced by heating the sheet member. In one embodiment, the sheet member may be positioned substantially parallel to the surface of the support, preferably at the bottom region of the dielectric window. Alternatively, the sheet member may be cylindrical. In such an embodiment, the apparatus may further comprise means for providing a gas (etch or deposition) to the chamber on either or both sides of the cylinder; this will depend on whether an etch step or a deposition step is in progress.

The sheet member may be located part way down the dielectric portion and may be supported in any suitable manner. For example, it may be supported from the lid of the chamber by means of a first supporting member and/or from below the dielectric portion by means of a second sheet supporting member. The sheet supporting members may be formed of any suitable material, but one example is a slotted conducting material. In such an embodiment, this

may provide the added benefit of acting as a Faraday shield to reduce the coupling between the source and bias components of the plasma. Alternatively, two dielectric portions of the chamber may be provided (a first and a second dielectric portion) having the attenuation means positioned therebetween. This allows a more practicable means of electrically biasing the sheet member and the general concept is also transferable to other geometries of the process apparatus.

Two or more antennae may be positioned externally adjacent the dielectric portion or portions and at least one antenna preferably lies above the level of the attenuation means, and at least one antenna lies below the level of the attenuation means. In such an embodiment, the chamber may be provided with an inlet to provide a gas or gases above the level of the attenuation means and a further inlet for providing a gas or gases below the level of the attenuation means.

According to a second aspect of the present invention, there is provided a method of etching a feature in a substrate in a chamber by means of a plasma, the method comprising striking a plasma in the chamber and reducing and/or homogenising the ion flux from the plasma substantially without affecting the radical number density.

The method may comprise the step of alternately etching the substrate by means of a plasma and depositing a passivation layer on the substrate by means of a plasma.

For high etch rates, the number of radicals needs to be

increased, and this may be achieved in a number of ways:

(a) By increasing the source power, the precursor gas dissociation fraction is increased. For example, SF_6 --> SF_x+yF. However, the efficiency is limited in terms of the number of fluorine radicals released from each SF_6 molecule, i.e. two fluorine radicals are readily liberated. However, the stability of the dissociates and recombination reactions limit release of more than two fluorine radicals from each SF_6 molecule. Even so, the etch rate can be significantly enhanced by the method of increasing the source power to effectively dissociate a greater number of SF_6 molecules. Once saturation occurs with respect to the fluorine radical yield, further rate enhancement can only be achieved by increasing the gas flow rate in proportion to the RF power;

(b) As pressure is increased, the radical number density increases as the number of collisions increases. But as the pressure is increased, the plasma density in low pressure high density systems can be reduced due to the "scattering" collisions which reduce the degree of confinement. Also pressure increase reduces etched profile anisotropy, as collisions impair the degree of directionality of ions. The result is profile deterioration through "bowing" etc, which becomes worse as the aspect ratio increases. Therefore, this method is also limited in application.

A means for overcoming the limitations and further enhancing the etch rate is by using a high power pulsed source. By using <u>very</u> high power pulses (ref. GB-A-2105729; G. Scarsbrook, I.P. Llewellyn and R.A. Heinecke. J. Vac Sci.

Technol. A&(3), May/June 1989; and I.P. Llewellyn, G. Scarsbrook and R.A. Heinecke. SPIE Vol. 1148 Nonlinear Optical Properties of Materials (1989)) complete gas dissociation can occur, resulting in total fragmentation of the precursor.

Thus, according to a third aspect of the present invention, there is provided a method of etching a feature in a substrate, the method comprising applying pulsed high power to an etch source gas, and alternately etching the substrate by means of a plasma and depositing a passivation layer on the substrate by means of a plasma in a chamber.

The high power is preferably applied for between 100 microseconds and several milliseconds during each pulsed cycle. In a preferred embodiment, the power density of the pulsed high power is between 10 and 300 W/cm^3.

The method may further comprise the step of reducing and/or homogenising the ion flux from the plasma substantially without affecting the radical number density and, for example, any of the above-mentioned methods can be used.

According to a further aspect of the present invention, there is provided a plasma processing apparatus for performing the above method, the apparatus comprising a first chamber having an inlet for an etch source gas and a second chamber having a support for a substrate, wherein the first and second chambers are connected via an aperture, and wherein the apparatus further comprises a means for providing pulsed high power to the first chamber.

The pulsed high power discussed below is RF, but any power may be used, for example microwave or DC.

In one embodiment, the first chamber may comprise a dielectric window and the means for introducing the RF pulsed high power is an antenna which is preferably positioned externally adjacent the dielectric window.

The second chamber may be actually separated by a separating member from the first chamber and indeed more than one first chamber providing a pulsed source may be used.

The second chamber may have a separate gas inlet.

Preferably, the plasma processing apparatus further comprises attenuation means which may be in the region of the aperture. This attenuation means may be the same as the forms mentioned above, but is preferably in the form of magnets placed on either side of the aperture to form a magnetic filter. This improves the confinement of the pulsed plasma within the source. Alternatively, magnets may be located in tubes across the aperture in, for example, a similar configuration to that described above.

In one embodiment, a restricted conductance aperture connects the first and second chambers which allows a higher source pressure to be practically utilised.

According to a further aspect of the present invention, there is provided a method of etching a feature in a substrate, the method comprising applying a high density radical source to an etch source gas, and alternately etching the substrate and depositing a passivation layer on

the substrate in a chamber.

The etch and/or deposition steps preferably take place by means of a plasma.

Although the invention has been defined above, it is to be understood that it includes any inventive combination of the features set out above or in the following description.

The invention may be performed in various ways and a specific embodiment will now be described, by way of example, with reference to the accompanying drawings, and in which:

Figure 1 is a cross-section of a plasma processing apparatus according to the present invention;

Figure 2 is a cut-away plan view showing the magnet array of Figure 1;

Figure 3 shows an alternative apparatus of the present invention in cross-section;

Figure 4 shows a plan-section of the embodiment in Figure 3;

Figure 5 shows a cross-section of an alternative apparatus;

Figure 6 shows a cross-section of a further alternative apparatus;

Figure 7 shows a cross-section of a further embodiment of the apparatus;

Figure 8 shows a cross-section of a further alternative embodiment;

Figure 9 shows a cross-section of a further alternative embodiment; and

Figure 10 shows an enlarged cross-section of one embodiment of the aperture.

Referring to Figure 1, there is shown a plasma processing apparatus generally at 1. The apparatus 1 comprises a chamber 2 into which an etch or deposition gas (or both) may be passed through inlet 3 in its lid 4. Extending through the base 5 of the chamber 2 is a platen 6 on which is mounted a wafer 7, for example a semiconductor wafer. The chamber 2 has a side wall 8 the upper region of which is formed of a dielectric window 9. An antenna 10 is located outside of the dielectric window 9 and is used to inductively couple RF power into the plasma which is formed inside the apparatus. The frequency of the RF power is 13.56 MHz, but other frequencies may also be used. In the embodiment shown, in use etch and deposition gases are fed alternately through inlet 3 depending on which of the etch or deposition step is in progress. The platen 6 is energised from a second RF supply.

Within chamber 2, a series of parallel tubes 11 are mounted in a plane parallel to the surface of the platen 6. Each tube contains a small permanent magnet or series of magnets arranged as shown in Figure 2. Forced air, water or other suitable cooling medium is passed through the tubes to ensure that the magnets are not subjected to high temperatures. The cooling medium is distributed by means of a manifold 13.

In an alternative form, the permanent magnets 12 may be replaced by current carrying conductors in tubes, as

mentioned above, arranged in such a way as to create electromagnetic fields of similar strengths and orientations to those achieved by the permanent magnets. As a further variant, the use of a hybrid of permanent magnets and electromagnets is also envisaged. The principle of operation is that electrons from the plasma created near the antenna 10 move into the region of influence of the magnetic field, are guided by the magnetic field and lost to the wall 8 or manifold 13 due to an E x B drift. The electric field set up in the plasma by the loss of electrons ensures that ions are also attracted to the wall or manifold where they too are lost. The net result is a reduction in plasma density on transitting the magnetic field from the region in which the plasma is produced to the region in which the wafer is placed. The magnetic field has no effect on the radicals, and the magnet carrying tubes have only marginal effect on the radical numbers due to a small degree of recombination on the surface. The magnet carrying tubes and/or manifold may be electrically biased if appropriate.

Use of this magnetic attenuator allows high RF powers to be applied to the plasma source, producing the high numbers of radicals needed for a high etch rate, but limits the number of ions which can reach the wafer so that the physical component is homogeneous and well controlled. Benefits include not only utilisation of high source power plasmas (allowing high etch rates), but also of enhancing the uniformity of the etch.

Figures 3 and 4 show a variation in the apparatus in

which identical reference numerals correspond to the identical parts. In the embodiment shown, permanent magnet carrying tubes 14 extend vertically and are placed in a "cage" arrangement to form an internal magnetic "bucket", with each tube substantially parallel to the dielectric window 9 and side wall 8. The principle of operation is the same as that described with reference to Figures 1 and 2 above. In Figure 3, the tubes 14 are shown as terminating at their upper ends in the lid 4 of the chamber 2 and at their lower ends in a plate 15 having a central aperture 16. However, it should be noted that the upper ends of the tubes 14 need not necessarily terminate in the lid of the chamber, and may alternatively terminate in a similar plate to that used to locate the lower ends. The plate 15 or lid 4 allows the tubes 14 (which are normally conducting) to be electrically biased or grounded. The tubes 14 will provide a degree of electrostatic screening in addition to the magnetic filter structure and therefore will assist in decoupling the plasma generation local to the antenna from ion acceleration to the wafer which is brought about by the RF bias applied to the platen 6.

The magnet carrying tubes 14 may be air or fluid cooled, and if so will require suitable manifolds or interlinking at top and bottom ends.

Corresponding to the planar magnetic filter, the permanent magnets may again be replaced by current carrying conductors in a suitable configuration of tubes to form an equivalent electromagnetic field. In addition, a hybrid of

permanent and electromagnets may be used to form the required field pattern. Also shown in Figure 3 is a second inlet 16 and this inlet 16 and inlet 3 may be attached to one or more distribution systems in order to feed the chamber with etch and/or deposition gases.

Figure 5 shows a further alternative arrangement. In the embodiment shown, outside chamber 2 are positioned strong magnets 17 adjacent sidewall 8 just below the level of the dielectric window 9. The strong magnets 17 create a long range magnetic field. This arrangement is simpler and cheaper to construct, but suffers from the disadvantage that the magnetic field will have a significant magnitude throughout a sizable part of the apparatus. This may affect the plasma production region and perhaps more seriously, may result in a significant magnetic field strength at the wafer surface. The magnetic field may be created by permanent magnets or electromagnets, or a combination of both.

Figure 6 shows an alternative arrangement in which a horizontally disposed grid 18 is located across the chamber 2 separating the plasma production region adjacent dielectric window 9 from the wafer 7. The grid 18 has apertures 19 of varying sizes at different positions and may have solid sections with no apertures. The effect of the grid 18 is to attenuate the ion flux reaching the wafer due to ion loss on the grid 18, as described above.

Figure 7 shows a variation of the design described with reference to Figure 6. In this embodiment, grid 20 having apertures 21 is cylindrical (for a cylindrical process

chamber). Gas may be fed in at either or both inlet 3 or second inlet 16 depending on whether a deposition step or an etch step is in progress. As described with reference to Figure 3, the grid 20 may or may not extend all the way from the lid 4 to the bottom of the dielectric window 9.

A more complex form of the plasma processing apparatus is shown in Figure 8. A grid 18 is located part way down a dielectric window 22. The grid 18 may be supported from the lid 4 or from below the dielectric window 22. As above, the grid 18 may have a number of identical apertures in it or may have sections with larger apertures or sections which are blanked off with the aim of producing spatial improvements in the uniformity of the overall etch at various positions on the wafer 7. Two antennae 23, 24 are wound around dielectric window 22, antenna 23 being positioned above the level of grid 18 and an antenna 24 being positioned below it. Gas is fed through inlet 3 to the chamber and a further gas inlet 25 feeds a gas ring 26 or similar gas distribution device located below grid structure 18. As before, the wafer 7 is supported on a platen 6 near the bottom of the chamber.

With the similar plasma processing chambers shown in Figures 6 and 7, passivating material may be deposited on the grid structure during the deposition step. This effect may be reduced by ensuring that the grid structure is heated, but there may still be a need for enhanced passivation when the grid structure is present.

For the apparatus shown in Figure 8, the preferred

method of operation is as follows. For the etch step, gas is fed into inlet 3 and antenna 23 is energised. Radicals pass through the grid structure 18 down to the surface of the wafer 7, while the positive ions are attenuated and their spatial distribution modified by the grid structure. If found to be of benefit, antenna 24 may also be energised at a low power level, and some gas used in the etch step may be introduced through gas inlet 25. For the deposition step, the appropriate gas is fed to gas inlet 25, and antenna 24 is energised. It would not normally be necessary to energise antenna 23 or feed gas into inlet 3 during the deposition step of the process.

For the apparatus shown in Figure 8, the grid structure 18 may be replaced with a magnetic attenuator of any of the above forms, with the operating scenario essentially unchanged.

As discussed above, a means for further enhancing the etch rate is to use a high power pulsed source. By using very high power pulses, complete gas dissociation can occur, resulting in total fragmentation of the etch gas precursor. Thus, for example, where SF_6 is the etch gas, complete gas dissociation occurs as follows:

$$SF_6 \text{ ---> } S + 6F$$

Typical pulse RF power levels and pulse duration are of the order of 50 kW and 200μS respectively, but the pulsed power required is a function of the source size, and requirements may be as high as 200 - 300 W/cm^3 to achieve high dissociation of the gas. The range of conditions that

are relevant here include 100μS to several mS pulse duration and 10 to 300 W/cm^3 power density, depending on the degree of dissociation enhancement required. The source may comprise cooled members to enhance sulphur condensation on to the surface.

Figure 9 shows an apparatus for achieving this. In the embodiment shown, an aperture 27 is present in the lid 4 of chamber 2. Extending from the aperture 27 is a subsidiary chamber 28 having dielectric window sidewalls 29 around which is wound antenna 30. The subsidiary chamber 28 has an inlet 31 in its upper surface for providing the etch gas. Also positioned in the lid 4 of chamber 2 is inlet 32 through which is provided the passivation gas or an etch related gas. Antenna 10 around dielectric window 9 forms the passivation or etch plasma as above. The subsidiary chamber 28, dielectric side walls 29, antenna 30 and inlet 31 together form a high power pulsed source generally shown at 33. The aim is to produce copious numbers of radicals within the pulsed source 33 which then diffuse into the main process chamber. In order to improve the confinement of the pulsed plasma within the source, magnets 34 are positioned either side of the aperture 27 to form a magnetic filter. Alternatively, magnets may be located in tubes across the aperture in a similar configuration to that shown in Figures 1 and 2, for example, for dividing the main process chamber 22.

Figure 10 shows an alternative embodiment in the region of the aperture 27. In this embodiment, the lower portion

of the subsidiary chamber comprises walls 35 which converge at their upper end opposite the end at aperture 27. Although the Figure shows tapering of the dielectric section, this alternatively may be of metallic construction, possibly as an extension of the separating member structure. This provides a low pumping conductance aperture and, in such an embodiment, the pressure in the pulsed high power plasma source may be increased without having a detrimental effect on the pressure in the main process chamber 2.

The aim of the embodiments presented in Figures 9 and 10 is to create a high radical density source which can provide a means for carrying out the etching step while the deposition plasma source is separated. The high pulsed power source presented above can be replaced by any high density radical source (whether plasma or non plasma). When this source produces undesirable electrically charged components, the attenuation means described above can be effectively used to restrict their transmission to the wafer. But where the source predominantly generates radicals only, such attenuation means would not be necessary. Here, the scope of the invention reverts to the use of a high radical source comprising the etch step species generation within the etch/deposition cyclic processing regime.

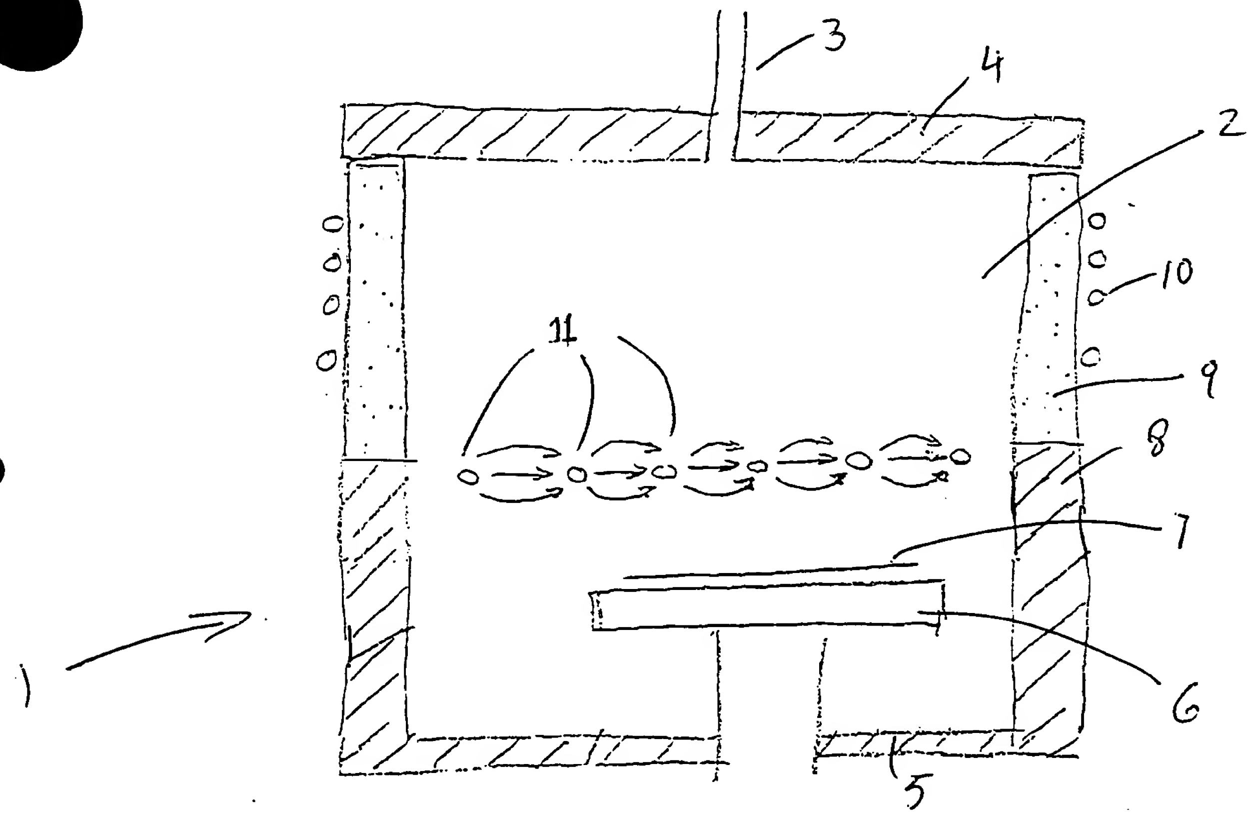

Figure 1

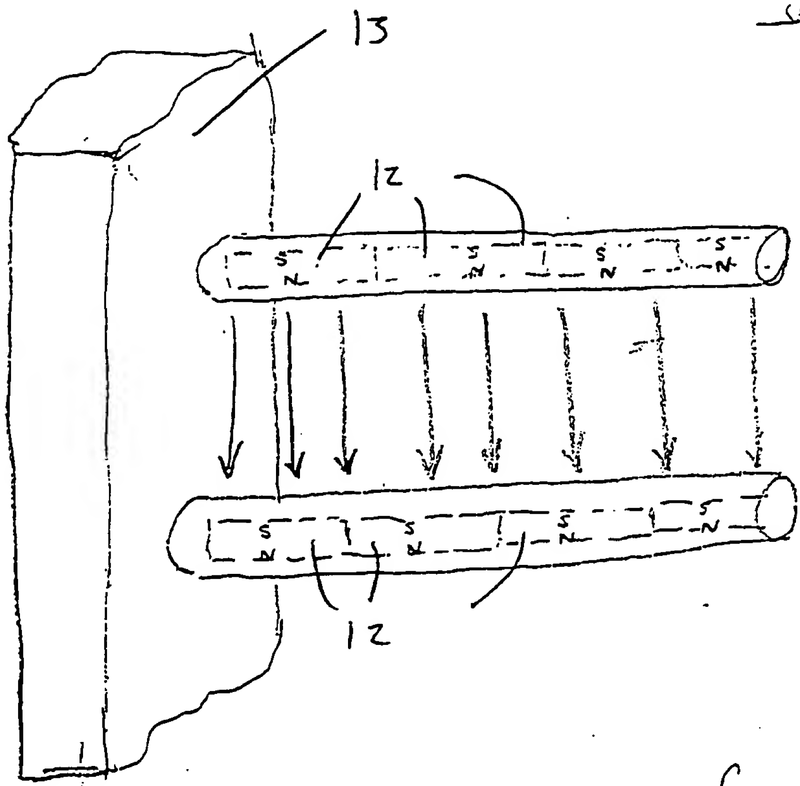

Figure 2

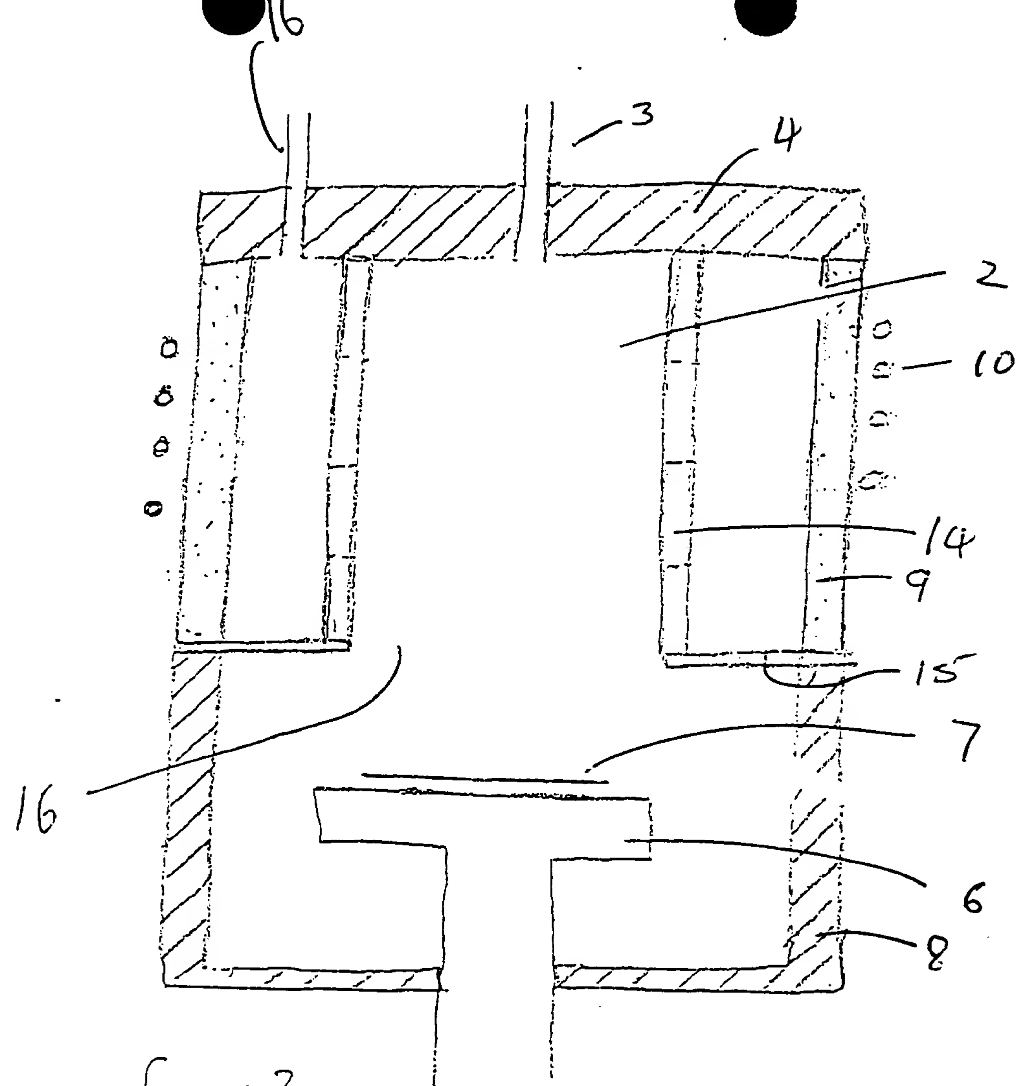

Figure 3

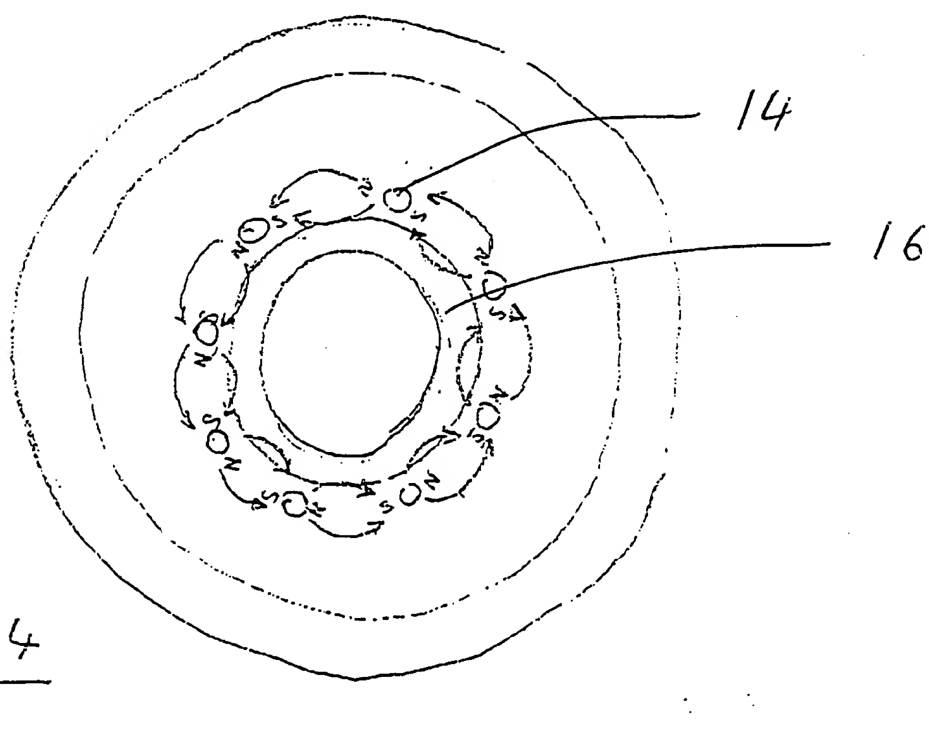

Figure 4

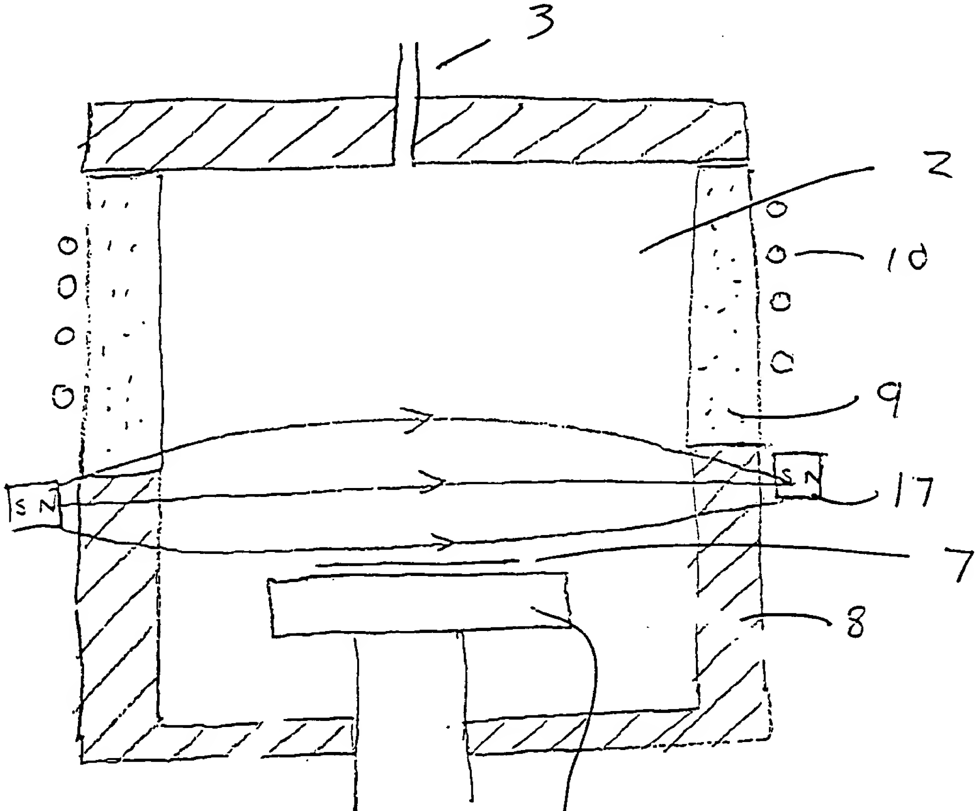

Figure 5

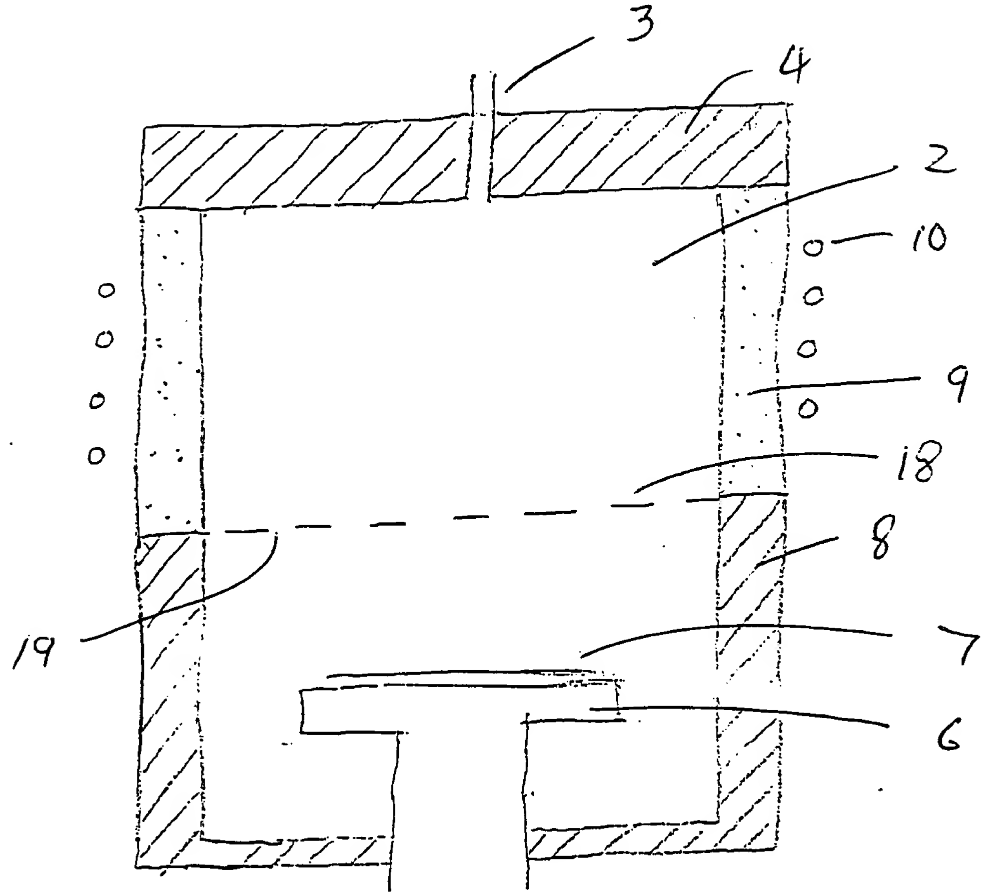

Figure 6

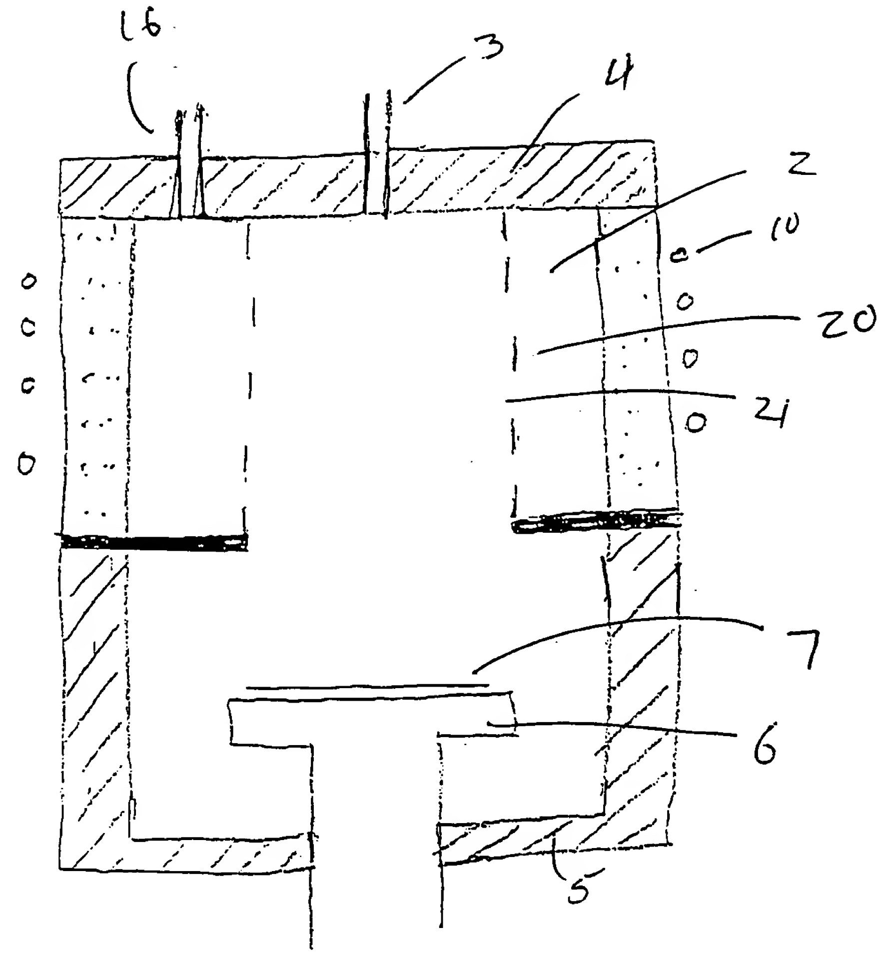

figure 7

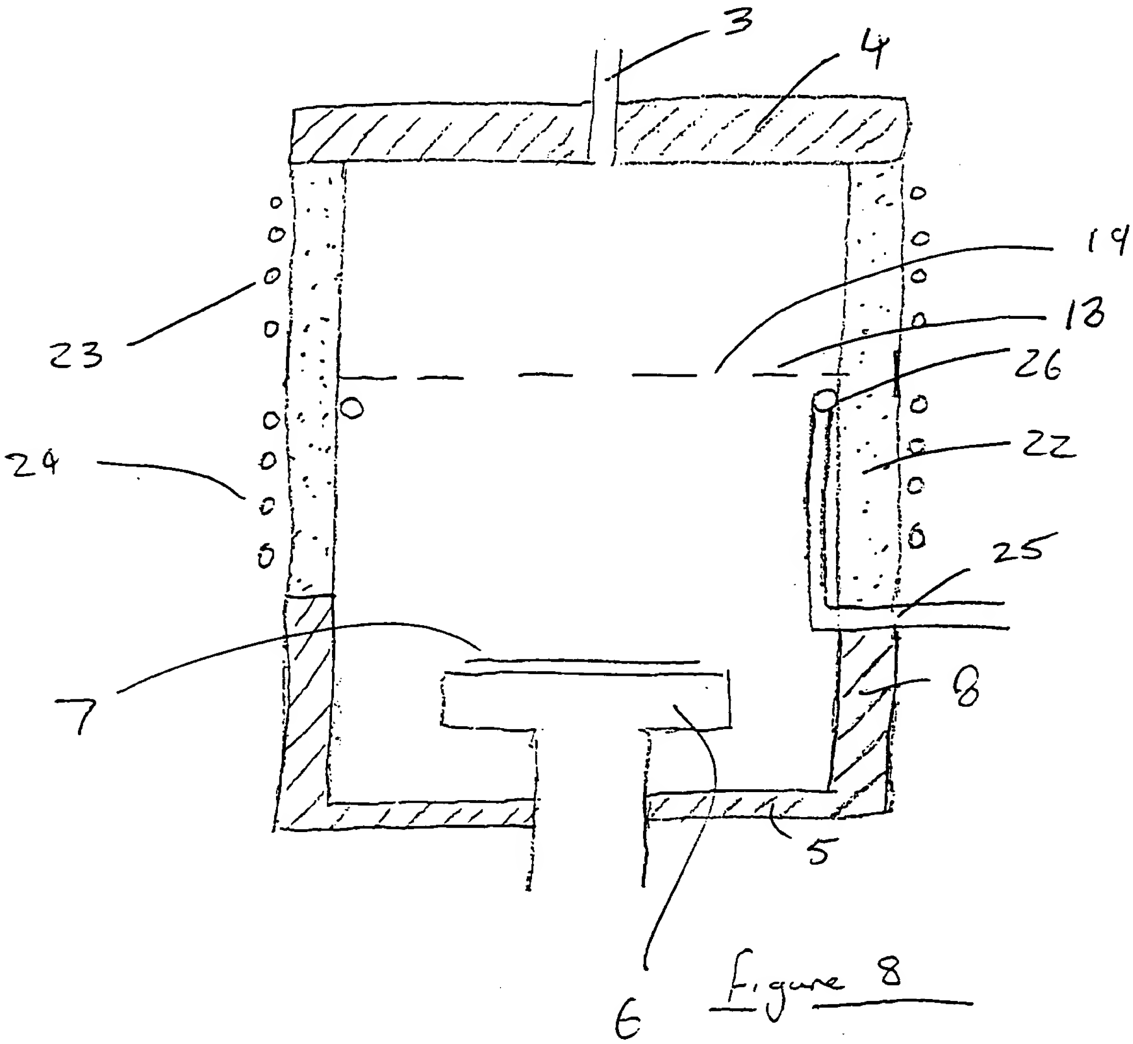

Figure 8

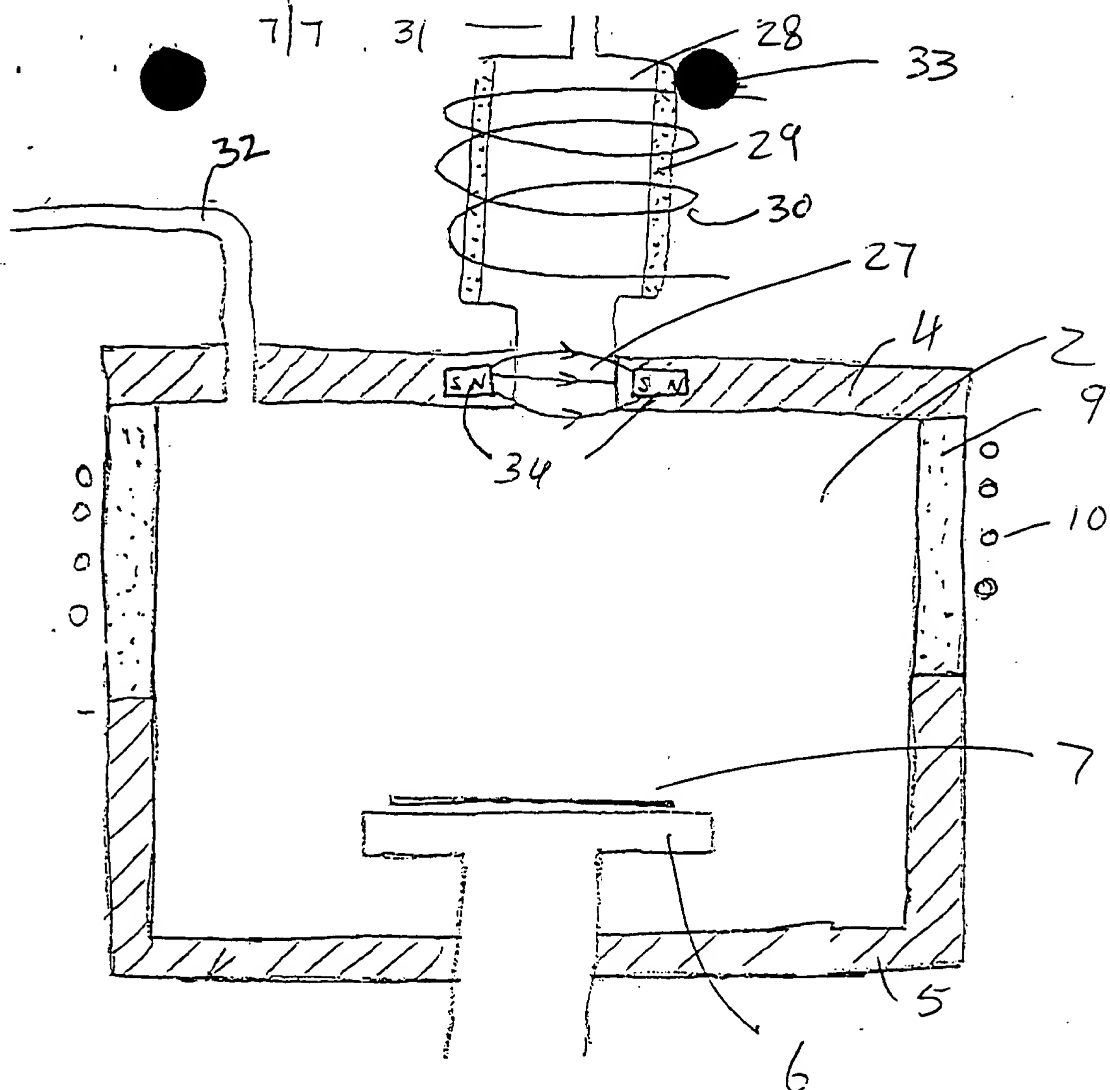

figure 9

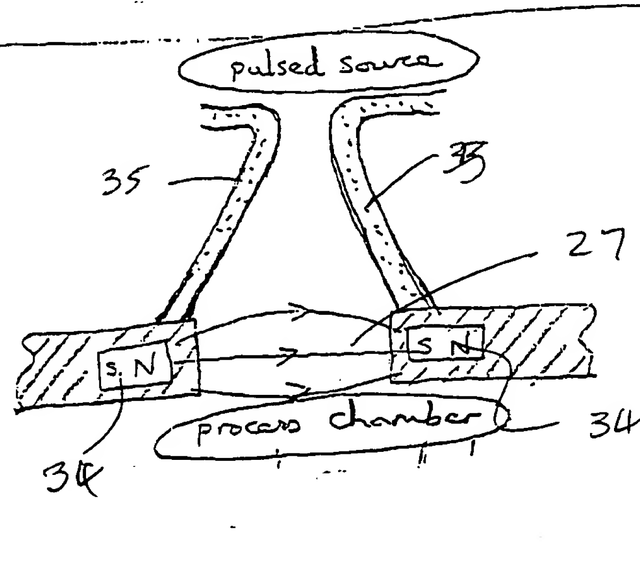

figure 10

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Wynne-Jones Laine & James.